

Shuttle Retrun-To-Flight IH-108 Aerothermal Test at CUBRC – Flow Field Calibration and CFD

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Abstract

This paper discusses one specific aspect of the Shuttle Retrun-To-Flight IH-108 Aerothermal Test at CUBRC, the test flow field calibration. It showed the versatility of the CUBRC LENS II wind tunnel for an aerothermal test with unique and demanding requirements. CFD analyses were used effectively to extend the test range at the low end of the Mach range. It demonstrated how ground test facility and CFD synergy can be utilized iteratively to enhance the confidence in the fidelity of both tools. It addressed the lingering concerns of the aerothermal community on use of impulse facility and CFD analysis. At the conclusion of the test program, members from the NASA Marshall (MSFC), CUBRC and USA (United Space Alliance) Consultants (The Grey Beards) were asked to independently verify the flight scaling data generated by Boeing for flight certification of the re-designed external tank (ET) components. The blind test comparison showed very good results.

A more comprehensive discussion of the topics in this paper can be found in Chapter 6 of Reference [1]. The overall aspect of the test program has been discussed in an AIAA paper by Tim Wadhams [2]. The Shuttle Ascent Stack performance and related issues discussed in the Report [1] are not included in this paper. No ITAR data is included in this paper.

1. Shuttle IH-108 test overview

The STS-107 Columbia accident has necessitated the need to re-evaluate the Space Shuttle Vehicle (SSV) design. The Columbia Accident Investigation Board concluded that foam shed during ascent from external tank impacted leading edge of the left wing causing damage. One of the re-design is to remove Bipod fitting TPS foam ramp to eliminate debris source. The bare metal bi-pod fitting was never flown before without TPS cover. It is one of the most critical component in the Shuttle Return-to-flight re-design effort. Boeing is under subcontract to United Aerospace Alliance (USA) to provide the aerothermal environment for the bi-pod fitting and associated components.

In July 2004, NASA management approved the request to conduct the IH-108 aerothermal wind tunnel test and made it a Return-to-flight requirement. With a March 2005 launch schedule, it meant that the test team had less than five months to develop and conduct the test and test data analysis. The details of the bi-pod re-design challenge and its aerothermal environment generation were discussed in companion papers. This presentation will focus on the preparations for the IH-108 test and a summary discussion of the test data evaluation.

The IH-108 aerothermal wind tunnel test is conducted at the CUBRC LENS-II shock tunnel at fully duplicated Mach 3.5 and Mach 4 flight conditions using a 3.5% scale integrated vehicle model. The total model length measured 84.5 inches long. The CUBRC tunnel allowed testing at actual flight Mach number, Reynolds number and enthalpy or enthalpy ratio for the first time in Shuttle program history. The heat flux gage is unique because it can be customized to test components as small as 0.040" in size for the 3.5% scale model. The test data set provided detailed heating environment data of small components that never had direct data before. It discovered several "hot spots" around the bi-pod structure that could not be resolved before. The test data had been used to verify the bi-pod aerothermal environment and updated the analysis model. It is used to help certify that the new bi-pod design is safe to fly the STS-114 mission.

2. Aerothermal design challenge

The IH-108 wind tunnel test was recommended and approved to validate the heating environments on the External Tank (ET) bipod fittings and surrounding acreage. A set of objectives was identified and then used to develop requirements that would ensure proper data were collected to fulfill such objectives. These requirements were then utilized to select the appropriate model and test facility for this test program.

The primary objective of this test was to obtain heat transfer data to verify the design heating environments in the critical area of the redesigned ET bipod fitting region, including the nearby Liquid Oxygen (LO₂) feedline components, ET/Orbiter bipod strut and acreage region. In addition, pressure data were required to provide a better definition of the complex flow field in this area and to calibrate the current CFD models. Additional information on the entire region upstream of the ET bipod assembly was needed to completely understand the flow mechanisms that were affecting the conditions in its vicinity.

In addition, it was required that the test conditions matched or exceeded the parameters used for design certification of the vehicle, especially for the range of peak heating in the vicinity of the ET bipod fitting.

3. The IH-108 Test Program

3.1 CUBRC test facility simulates actual flight parameters

In order to develop design heating models (or Body Points (BPs)), the test conditions needed to simulate Performance Enhancement Certification (PE-Cert) Trajectory level parameters such as Reynolds number, Mach number, pressure, etc. for the range of peak heating in the ET bipod fitting region. Data were also needed at actual flight conditions to develop an improved, more accurate flight-scaling factor for the new heating models. The STS-4 and STS-7 Best Estimated Trajectories (BETs) were used along with the design trajectory to define the ranges for each parameter that were to be tested to successfully complete the previously defined objectives.

3.2 Special gage and instrumentation of small components

In order to achieve the aforementioned test objectives, it was required for the selected test facility to be able to obtain pressure data as well as heat transfer data, especially in the ET bipod fitting

region. In addition, the test facility should be able to install instruments on small protuberances such as the ET bipod fitting, struts and yoke, as well as the LO₂ feed line acreage and bracket near the ET bipod. In order to reduce the uncertainty in the heating environments for the ET bipod region, a high-fidelity full-stack (Orbiter, External Tank, Solid Rocket Boosters) wind tunnel model was required to simulate the complex flow field in this area. Thus, the External Tank (ET) model needed to simulate all major protuberances upstream and in the vicinity of the ET bipod, including the Intertank stringers (corrugated surface), LO₂ and LH₂ Protuberance Air Load (PAL) ramps, LO₂ cable tray and Ice/Frost ramps, and LH₂ feed line. These protuberances as well as the complex ellipsoidal shape of the ogive were to simulate the latest ET configuration (ET-123). Figure 1 provides an overview of the External Tank.

In addition to the level of detail, the model scale was also required to be greater than that used for previous tests (0.0175-scale). This was necessary to allow sufficient instrumentation be installed on the small protuberances and surrounding acreage in order to better understand the flow characteristics and heating gradients that resulted from the ET bipod redesign. The selected test facility was required to provide the appropriate test conditions and at the same time accommodate the 0.035-scale wind tunnel model. CUBRC LENS II had the unique capability to test at the desired test conditions (Mach range , Re/ft and Tw/To) and the data acquisition capability (both pressure and heating data) based on proven methods.

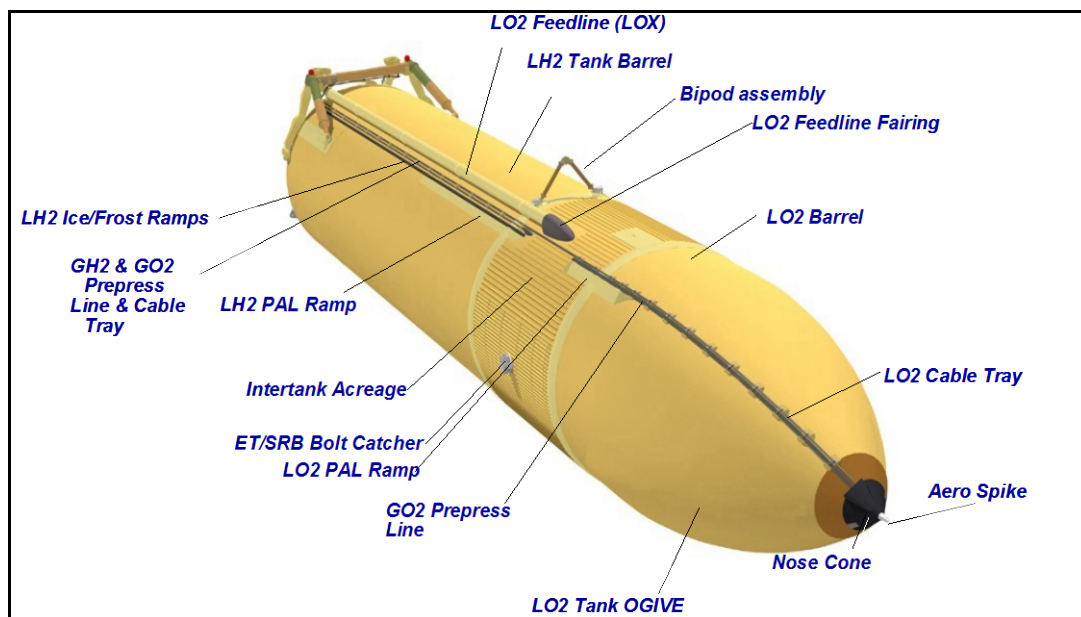


Figure 1 Overview of External Tank Configuration

3.3 Data reduction and quality in LENS II Tunnel

During the past 15 years, two large new ground test facilities, LENS I and II, have been constructed by CUBRC and successfully employed to directly replicate flight conditions on full-scale interceptors flying at velocities from 3,000 ft/sec to 15,000 ft/sec at altitudes from 10,000 to 200,000 ft. The construction of these wind tunnels was driven by the need to conduct fundamental research as well as design and evaluate hypersonic vehicles whose performance were controlled by complex flow phenomena, such as boundary layer transition, compressible

turbulent shear layer mixing, shock/turbulence interaction and “real gas” combustion chemistry, all of which are poorly understood and cannot be accurately predicted. Furthermore, such flows cannot be easily scaled. For example, the non-equilibrium fluid dynamic and chemical process which occurs in regions of boundary layer transition and “real gas” flow chemistry can only be replicated with any accuracy on full-scale test articles under fully duplicated free-stream conditions. The LENS II tunnel was constructed specifically to conduct full-scale testing of high speed vehicle systems that operate at velocities from 3,000 ft/sec to 7,000 ft/sec at altitudes from 10,000 ft. to 120,000 ft. The tunnel has been used in aeroheating studies conducted with full-scale vehicles at full-duplicated flight conditions for the Standard Missile, HyFly, and X-51 programs and provided aerothermal heating and dynamic shroud separation data that directly duplicates those heating environments that are generated under actual flight conditions.

4. Flow-field Calibration and Blockage Tests

The test conditions to be simulated in the proposed IH-108 test program were discussed in Section 2. Based on the free-stream conditions for the selected Performance Enhancements Certification (PE Cert) trajectory, the peak convective heating for the full-stack, integrated-vehicle OTS configuration on and around the bipod fitting occurs when the Mach number is close to 4.0. The LENS II facility provided the only tunnel capable of replicating the required Mach numbers, Reynolds numbers, and Total Enthalpy. To match the Reynolds number based on the vehicle length and the free-stream conditions for the PE Cert trajectory, the unit Reynolds number in the CUBRC LENS II facility should be 7.727×10^6 per foot. To match the Reynolds number based on the vehicle length and the free-stream conditions for the STS-4 trajectory, the unit Reynolds number in the CUBRC LENS II facility should be 2.65×10^6 per foot. A third test condition was proposed to simulate the Reynolds number for the Mach 4 tests (IH-97) that were conducted in the 1980s in AEDC’s Aero Thermal Tunnel C [Nutt et al. (1986)]. To match the Reynolds number based on the length of the 0.0175-scale AEDC model and the free-stream conditions for these tests, the unit Reynolds number in the CUBRC LENS II facility should be two million per foot.

Since all of the previous tests in the CUBRC LENS II facility were conducted at velocities higher than the Mach 4.0 required by the IH-108 test program, two new throats were designed and fabricated by CUBRC specifically for the IH-108 tests. One nozzle was to deliver Mach 4 flow in the test section; the second was to deliver Mach 3.5 flow. The design of these new throats was optimized using full Navier-Stokes solutions with chemical reactions. Before the IH-108 test program, a series of airflow calibration tests were conducted. These calibration runs were conducted:

- 1) to establish the flow properties over the range of test conditions identified in Section 2,
- 2) to calibrate the numerical tools available to fluid dynamics analysts by comparing the measurements from a series of calibration runs with the computed flow field solutions, and
- 3) to ensure that the boundary layer was fully turbulent in the wind-tunnel simulations just as the boundary layer was fully turbulent in flight. In addition it was important to match the ratio of boundary layer thickness to bipod height.
- 4) to look for evidence of flow blockage caused by the presence of a large model

A model simulating the forward section of the External Tank (ogive) was built, instrumented, and used in these calibration runs to check for turbulent flow. In addition, two blockage test runs were also conducted before the IH-108 test program. For these blockage tests, the full-stack (OTS) configured model was used, with a small number of gauges hooked up in the forward section of the elements (Orbiter, ET, SRBs).

4.1 Calibration Run Matrices

4.1.1 Measurements to Define the Free-Stream Flow

For the calibration tests, the stagnation pressure and enthalpy were obtained directly from pressure measurements behind the reflected shock and measurements of the incident shock Mach number. Free-stream conditions were obtained from survey rakes containing Pitot-pressure probes and stagnation heat-transfer gauges on hemispheres to verify the stagnation pressure behind a normal shock and total temperature, respectively. The actual rake is shown in Figure 2. High frequency pressure instrumentation is used in the Pitot probes. However, in regions where flows generate high thermal loads, thermal protection systems must be employed, which lower the frequency response.



Figure 2. LENS II IH-108 Flow Field Survey Rake

Other measurements that were made during the calibrations runs included cone and static pressure to verify free-stream static pressure. Hemisphere stagnation heat transfer rates were verified by Fay and Riddell stagnation heat transfer calculations [Fay and Riddell (1958)]. Total temperature probes were used to verify the total temperature of the flow. Total heat transfer measurements were made with miniature thin-film or coaxial sensors placed in the stagnation region of a hemispherical nose-tip.

4.1.2 Description of the Calibration Model

In addition to the measurements that were made during the calibration runs to define the free-stream conditions, pressure and heat transfer measurements were also provided over a simplified ogive model that was installed on the LENS II calibration rake (see Figure 2). These data were used:

- 1) to calibrate the numerical tools available to the analysts by comparing the measurements from a series of calibration runs with the computed flow field solutions, and
- 2) to ensure that the boundary layer was fully turbulent in the wind-tunnel simulations just as the boundary layer was fully turbulent in flight.

The answer to the second issue is critical because, if boundary-layer transition did not occur naturally, it would be necessary to employ boundary-layer trips to produce a fully turbulent boundary layer for the lower Reynolds number flows during the IH-108 test program. A consensus opinion shared among test group members and the advisory group concurred that boundary-layer trips were to be avoided, if at all possible. The calibration model data would also provide a good reference for comparison with the “as run” conditions.



Figure 3. LENS II Calibration Ogive Model As Installed In Calibration Rake

The calibration ogive was built from the ET-123 External Tank CATIA model and truncated at a total length of 6.454 inches (model scale), which represents 10% of the External Tank length (see Figure 3). The model included the aero-spike, but not the LH₂ cable tray, GO₂ pressure lines and associated brackets and ramps. The model was instrumented with a nose-tip Pitot probe, four (4) surface pressure transducers on the 0° ray and eight (8) heat transfer gauges on the 180° ray.

4.1.3 Accuracy of Flow Calibration

As previously discussed, the IH-108 test required CUBRC to design tunnel hardware employing DPLR nozzle solutions to attain the desired conditions. The nominal exit Mach number for the LENS-II Mach 3.5 – 7.0 nozzle is 4.5, so the throat diameter of the nozzle was increased to bring the test Mach number down to a value of 4.0 for the first part of the test, and then again to 3.5 for the second part. The design of the throat modifications for the Mach 3.5 and 4.0 conditions were guided by computations with the DPLR code to produce satisfactory flow profile close to the target condition. During each calibration run, a rake of Pitot probes was placed in the free-stream just beyond the nozzle exit plane in the same x-location as the IH-108 bipod assembly to assess flow uniformity.

Pitot pressure is used as one measure of free-stream accuracy because: (1) it is a directly measurable quantity, and (2) it is sensitive to the momentum and velocity fluctuations in the flow field. Hence, it is an important, primary indicator by which to judge flow quality against desired standards of accuracy. From the Pitot tube and hemisphere stagnation temperature measurements, it is possible to determine the accuracy of the free-stream dynamic pressure and the stagnation point enthalpy to $\pm 5\%$ and the Mach number to $\pm 1.5\%$.

5 Numerical Tools for Generating Computational Fluid Dynamics Flow Fields

The availability of pressure and heat transfer data on a calibration ET ogive model prior to the actual IH-108 complete model test provided a tremendous opportunity for pre-test run condition evaluation. The Boeing team completed six (6) model scale ET ogive CFD runs before the calibration test. The Boeing pre-test runs used the projected free-stream conditions from CUBRC and were slightly different from the actual calibration conditions. NASA-JSC and CUBRC both generated CFD solutions from the “as run” calibration conditions. All ET CFD runs discussed in this section were run with a truncated, clean ET ogive (no protuberance components). The computational tools used by each team, as well as the studies/modifications performed to optimize their output, are discussed in this section.

5.1 Boeing - WIND

The CFD tool used by the Boeing team is the BCFD code, which has both structured and unstructured grid options. For this study, the structured grid WIND code was used. The WIND code was originally developed by Boeing as a general purpose CFD tool and is currently supported by NPARC Alliance [NPARC Alliance 2005]. The code supports multiple-zone handling with patched, overlapped or point-matched boundaries. It is a node-based finite volume algorithm with Van Leer, Roe, HLLC schemes and TVD options. The code is 2nd order spatial accurate and can be implicit or explicit in each direction. Local time stepping, time-accurate and global Newton iteration options are available. It can be run using ideal gas, Liu-Vinokur equilibrium air model, frozen flow or finite rate chemistry. Available turbulence models include Baldwin-Lomax [Baldwin and Lomax (1978)], Spalart-Allmaras one-equation [Spalart and Allmaras (1992)], Menter SST [Menter (1994)], and Chien k- ϵ [Chien (1982)]. For the current study, axi-symmetric 2-D and 3-D solutions were run, using Roe 2nd order scheme with TVD using a factor of 1. All turbulent runs were done with the SST model.

The computational grid for the three shuttle bodies is shown in Figure 4. The ET forward section is a tri-cone fitted to an ogive where strong shock-shock interaction was expected to cause massive flow separation around the tri-cone nose tip, or aero spike. The ET ogive grid was divided into four zones, which allowed the solutions to capture the diverse shock structure and still converge rapidly. The near surface zones used a high-density grid with slow stretching to assure good heat transfer results. This strategy proved to be very successful. Most solutions of the ET ogive were obtained overnight on single CPU Windows workstations without waiting for Linux cluster availability.

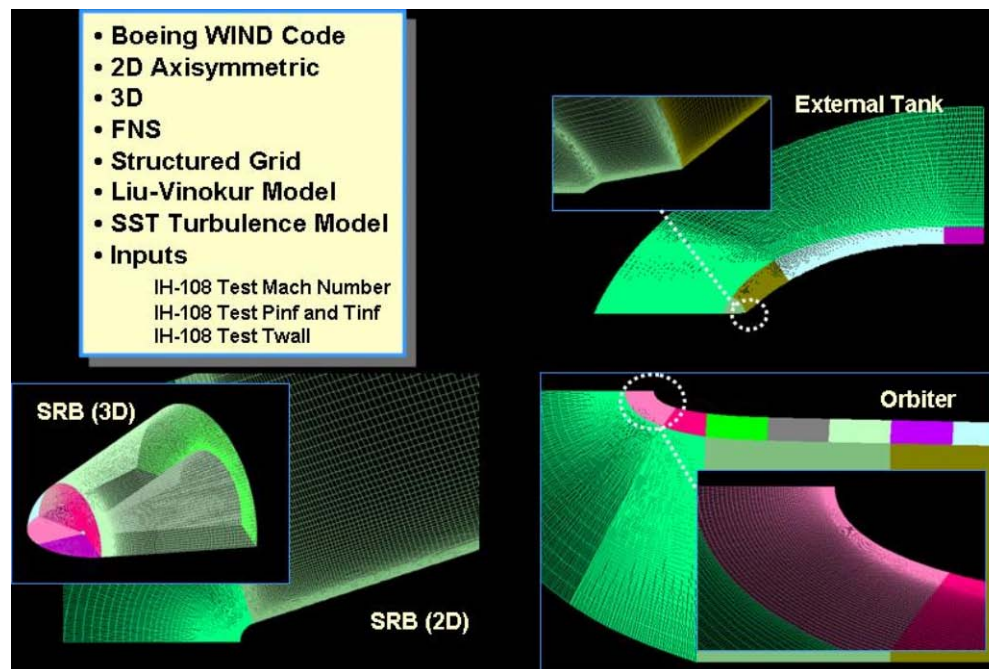


Figure 4. Boeing CFD Multiple Zone Grid Topology

In order to get good heat transfer results at the Mach/altitude combination of the PE Cert trajectory test conditions, the initial grid had a 0.0001-inch cell spacing off the surface based on previous Boeing experience. This spacing was found to be too tight and caused the solution not to converge sufficiently. The heat transfer magnitude and trend were all within expectation, but the distribution curve showed a “stair step” shape. A grid optimization study was conducted to find an optimal value of the Y^+ that would provide a smoother distribution of heat transfer and boundary layer properties in the stream-wise direction and, at the same time, a fast convergence of the solution. The original grid had a target cell Reynolds number (Y^+) of 0.1 and was found to cause convergence problems. Several Y^+ values were tested from 0.1 to 1.0. All Y^+ values larger than 0.5 were found to be too loose, resulting in an 18% over prediction in heat transfer. The Y^+ values of 0.2-0.3 were found to be optimal for this study. It must be emphasized that this grid study is not universal, but it is tailored to the specific ET ogive and the associated test conditions.

A quick examination of the Mach contour revealed that the solution using the revised grid captured the shock structure and the compression corner separation with good fidelity, as shown in Figure 5. Figure 6 and 7 compare the magnitude of the separation showing the distinctive shock structure between laminar and turbulent flow around the aero spike.

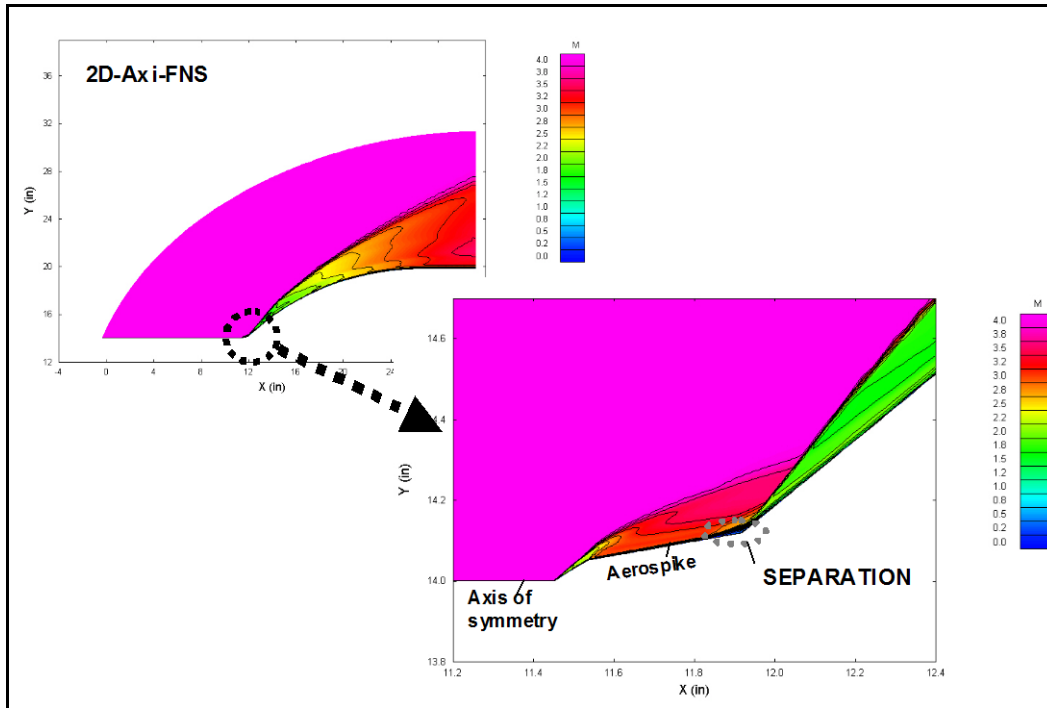


Figure 5. Typical ET Ogive Mach Number Contour in Mach 4.0 Turbulent Flow

Model Scale CFD (Laminar) To/Tw Conds., $M=4$, $AoA=0$, $\beta=0$

Pseudo-schlierens, c_p on body

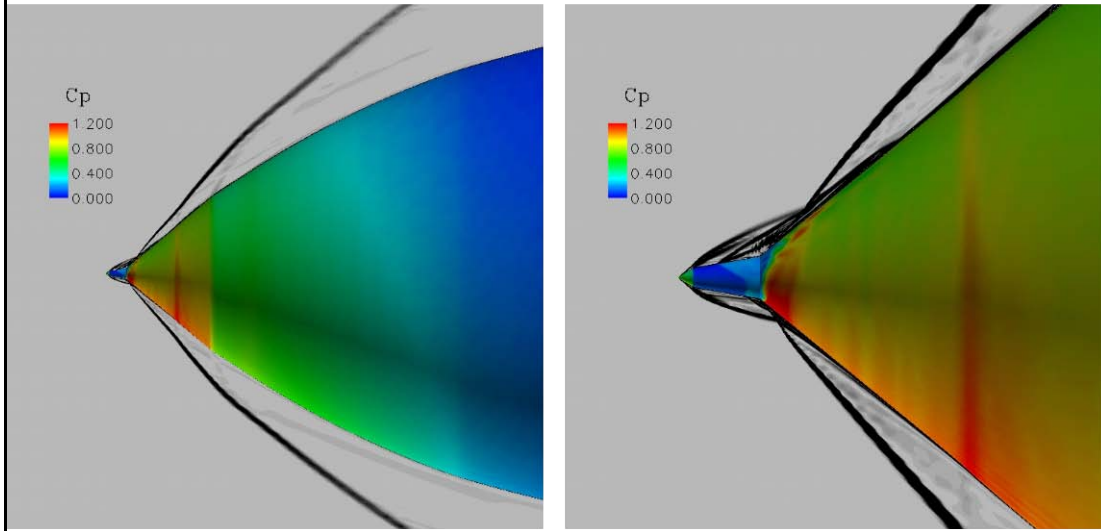


Figure 6. Laminar CFD Solution at Aerospike Junction

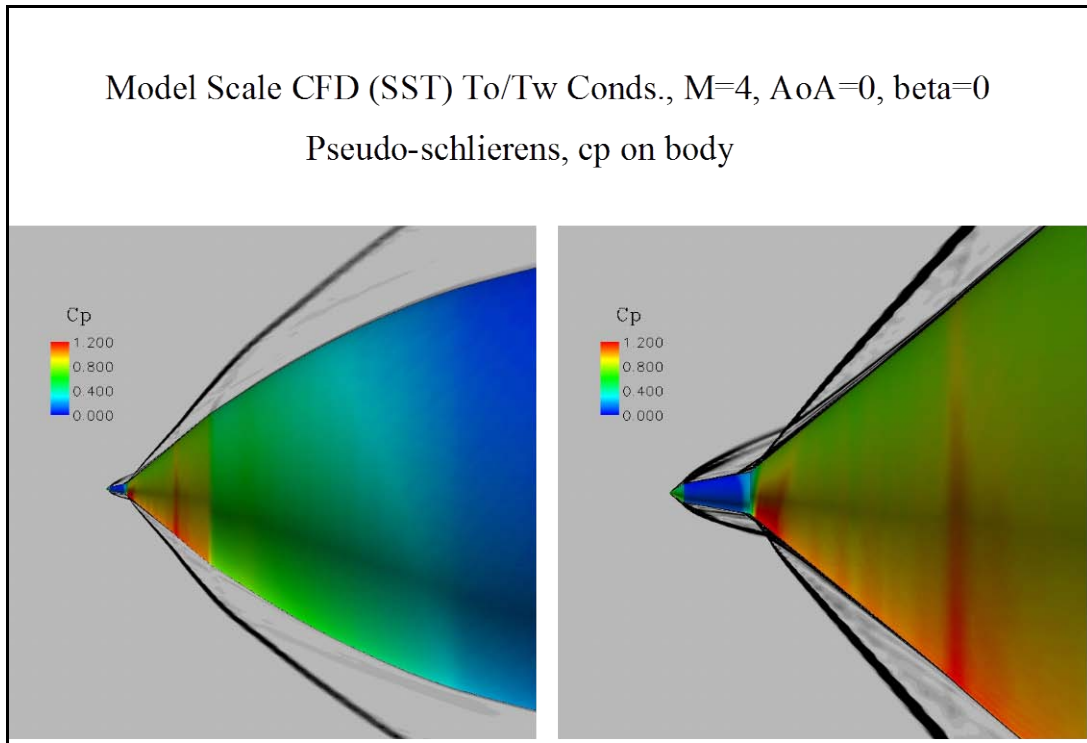


Figure 7. Turbulent CFD Solution at Aerospike Junction

5.2 NASA JSC - OVERFLOW

The NASA CFD analysis performed on the IH-108 calibration runs was done using the OVERFLOW code [Buning et al (2000); Jespersen et al, (1997)] on the ET ogive axi-symmetric grid. Each case was run fully turbulent using Menter's SST two-equation turbulence model [Menter (1994)]. The grid was truncated at $X_T = 562.5$ inches, just in front of the interaction region, to obtain undisturbed heating rates. Using the axi-symmetric assumption minimized the grid size to 360,000 points, which allowed a single condition to be run on one CPU in approximately 16 to 20 hours.

5.3 CUBRC - DPLR

The primary tool used by the CUBRC team is the Data Parallel Line Relaxation (DPLR) code [Wright, et al. (1998)] provided by NASA Ames Research Center. This code is a multi-block, structured solver that solves the full Navier-Stokes equations for two-dimensional, axi-symmetric, or three-dimensional flows. The code capabilities include vibrational, electronic, and rotational non-equilibrium, fully coupled, finite rate chemistry, as well as coupled radiation. Many of these thermo-chemical capabilities were not employed in this particular program. DPLR is a finite volume code with a modified (low dissipation) Steger-Warming flux splitting approach for the convection terms [MacCormack and Candler (1989)] and second-order central differencing for the diffusion terms. Turbulence models include the Baldwin-Lomax algebraic model [Baldwin and Lomax (1978)] and the Menter-SST 2-equation model [Menter (1994)], both of which are corrected for compressibility [Brown (2002)]. Data parallel line relaxation is used for time integration, providing an exceptionally fast and stable convergence behavior.

6 Flow Interference and Blockage

From the outset, the planners of the IH-108 test program focused on a model that was as large as possible to enable the instrumentation of small protuberances such as the bipod fitting. Since the scale of the integrated-vehicle model that had served as the workhorse of previous aeroheating wind-tunnel test programs was 0.0175, the planners focused on having the model scale for the IH-108 program be in the range of 0.030 to 0.035. Due to the size of the model, there was concern among some members of the test team, especially the senior advisory group, that the test data could be affected by blockage.

To allay these concerns, the test facility (CUBRC) performed a pre-test study to demonstrate that no blockage or other interference effects would be seen.

In addition to the pre-test flow interference analysis performed by CUBRC, two blockage test runs were conducted at Mach 4 at the low Reynolds number of $2.0 \times 10^6/\text{ft}$ to explore the capability to detect blockage effects experimentally. The blockage effect, if any, would be detected by abnormal surface gauge measurement. The actual test model, with some modifications, was used as the blockage model. These tests were conducted at Mach 4 because the nozzle throat was already in place from the calibration tests. The blockage tests also served to detect boundary layer transition on the three model elements (ET, Orbiter and SRBs).

The blockage test model was a partially instrumented IH-108 test model. Eight (8) heat-transfer gauges and three (3) pressure transducers on the ET ogive from the original instrumentation list were connected. Five (5) heat-transfer gauges and seven (7) surface pressure transducers were added to the ogive before the blockage test started. Five (5) pairs of heat-transfer gauges and pressure transducers were used to determine the location of an undisturbed flow area that could be used as a reference heat transfer location. A total of thirteen (13) heat-transfer gauges and ten (10) surface pressure transducers were activated on the ET ogive.

Six (6) heat-transfer gauges were installed on the lower centerline of the Orbiter, while five (5) heat-transfer gauges were added to the 270° ray of the solid rocket booster (SRB). These gauges were added to determine the boundary layer state on the forward location of these components. All gauges used in the blockage test remained active in all subsequent phases of the test program.

7 Boundary Layer Trip Analysis

As discussed in Section 7, one of the principal questions to be answered through the analysis of the calibration data was to ensure that the boundary layer characteristics in the wind-tunnel simulations accurately represented those seen in flight.

In earlier ground tests of OTS configuration, such as the 0.0175-scale model of the integrated vehicle for the IH-97 test, the boundary layers on the External Tank, on the Orbiter and on the SRBs were tripped to assure turbulent flow to obtain conservative aeroheating data. Questions were raised early in the IH-108 test program about the need to implement tripping. The NASA consultants (The Greybeards team) unanimously opposed using any boundary layer trips in the IH-108 test, as the planned test conditions would simulate actual flight parameters and, in turn, the resulting flow conditions would be representative of those seen in flight. However, there were different opinions about how soon the flow would transition to turbulent. The Boeing team conducted a quick study prior to the test, using both an engineering aeroheating code and CFD, in October and November 2004 to assess this problem. Simple and individual axi-symmetrical models of the ET, Orbiter and SRBs were used in the analyses to obtain answers regarding the boundary layer transition in a timely manner. In December and January 2005, the CUBRC team conducted a more comprehensive CFD study using 3-D models. The results of these studies and their comparison to the test data are discussed in this sub-section.

The value of Re_θ/M_e (Momentum thickness Reynolds number divided by the local, edge Mach number) was used to assess boundary layer transition behavior. In flight, the transition onset value for a sharp cone is 150 and for the Shuttle Orbiter is 280. In the CUBRC test facility, more conservative values of 125 and 220, respectively, are usually used. The ET nose section is an ogive shape similar to the Orbiter windward surface, so it was expected that the Orbiter onset criterion would apply to the ET. The SRB, in turn, is a slightly blunted cone-cylinder. Thus, the cone transition criterion should apply to the SRB.

The Boeing pre-test CFD cases included both laminar and turbulent runs at similar free-stream conditions. The Orbiter windward surface and SRB nosecone were also run in the same free-stream conditions. These flow fields were computed to assess the boundary layer state of all component bodies and to determine the need for boundary layer trips.

The heat transfer measurements on the ET ogive confirmed that the flow was fully turbulent immediately downstream from the location where the nose tip bow shock impinged on the ogive surface. From the calibration test schlieren pictures, it can be determined that the separation at the tri-cone compression corner was limited, which clearly indicated a turbulent flow field behavior early on.

From the above analyses and the calibration test data, the members of the IH-108 test team were confident that turbulent boundary layer existed on the ET surface for all test conditions. Thus, it was established that boundary layer trips were not required for the External Tank model.

8 Post-Test ET Ogive Data Comparison with CFD Results

To answer the two questions:

- 1) How do the measured values of the aeroheating parameters compare with the computed values?
- 2) Are the values (experimental and numerical) of the aeroheating parameters repeatable?

the test data from runs 8, 22, and 25, which correspond to the test condition #1, were examined. The nominal test conditions for these runs included a free stream Mach number of 4, a free stream unit Reynolds number of 7.8×10^6 per foot, and a wall-to-total-temperature ratio of 0.63 (TC #1). The values of the aeroheating parameters from these three runs will be compared with each other and with computed solutions generated by teams from Boeing, NASA JSC, and CUBRC. The analysis of each team as well as their conclusions is described in the following sub-sections.

The differences found between the computed flow fields and the Mach 4 test measurements were to be expected, as there were differences between the configuration used for the computations and the actual wind-tunnel model. The CFD solutions from all teams modeled a clean External Tank ogive, and thus did not simulate the viscous/inviscid perturbations to the flow as it encounters the different ET ogive protuberances (the gas oxygen prepress line and its fairing near the nose). The prepress line fairing may have had a shading effect that resulted in lower pressure and heat transfer measurements. It must also be noted that similar, though small, differences existed with all the high Reynolds number calibration runs that were tested with a clean, truncated ogive. The bias between CFD and test data remains unresolved. Nonetheless, post-test analysis showed excellent agreement between the measured and computed values, confirming that the desired test conditions at Mach 4.0 were achieved.

9 Conclusions

- 1) The requested free-stream test conditions were achieved within a reasonable range. The Mach 4.0 throat produces a very uniform test section Mach core with variation of 1% for 5 of the test conditions and one condition at 2% (Run 110, TC #2).
- 2) For the Mach 4.0 test conditions, the agreement between calibration test data and CFD is very good. The test team felt confident that the desired test conditions had been simulated and sufficient calibration data were available to corroborate it.
- 3) The calibration run heat transfer measurements on the ET ogive confirmed that the flow was fully turbulent immediately downstream from the location where the nose tip bow shock impinged on the ogive surface. Turbulent boundary layer also exists on the Orbiter windward surface in all test conditions. No boundary layer trip should be required for the ET or Orbiter model. The boundary layer state on the SRB, on the other hand, was not clearly defined by the test data.
- 4) The availability of ET ogive pressure and heat transfer data before the actual test commenced provided a tremendous opportunity for pre-test run condition evaluation.
- 5) All new test conditions using either new or existing nozzle hardware should be calibrated before the actual test is performed.
- 6) Good agreement among the CFD solutions from Boeing, NASA/JSC and CUBRC team was shown. The predictions are consistent at all Mach 4 conditions and typically over-predicted the test data by 10% to 20% on the ET ogive.

References for abstract:

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2. T.P. Wadhams, M.G. MacLean, M.S. Holden, and G.J. Smolinski, "Return to Flight Testing of a 3.5% Scale Space Shuttle OTS and OT Model at Mach Numbers of 3.5 and 4.0", AIAA Paper 2006-720, 44th AIAA Aerospace Sciences Meeting and Exhibit, January 9-12, 2006, Reno, Nevada.